Irrigation and Drainage Systems (2005) 19: 145–159

Controlled water table management as a strategy for reducing salt loads from subsurface drainage under perennial agriculture in semi-arid Australia

JOHN W. HORNBUCKLE[1,5], EVAN W. CHRISTEN[2], JAMES E. AYARS[3] & RICHARD D. FAULKNER[4]
[1]*Environmental Engineering Department, University of New England Armidale, NSW, 2531, Australia (E-mail: john.hornbuckle@csiro.au)*
[2]*CSIRO Land and Water, PMB No.3, Griffith, NSW, 2680, Australia*
[3]*Water Management Research Laboratory, USDA-ARS, 9611 S. Riverbend Avenue, Parlier, CA, USA*
[4]*Environmental Engineering Department, University of New England Armidale, NSW 2531, Australia*
[5]*Present address: CSIRO Land and Water, PMB No. 3, Griffith, NSW 2680, Australia*

Abstract. Recent community based actions to ensure the sustainability of irrigation and protection of associated ecosystems in the Murrumbidgee Irrigation Area (MIA) of Australia has seen the implementation of a regional Land and Water Management Plan. This aims to improve land and water management within the irrigation area and minimise downstream impacts associated with irrigation. One of the plan objectives is to decrease current salt loads generated from subsurface drainage in perennial horticulture within the area from 20 000 tonnes/year to 17 000 tonnes/year. In order to meet such objectives Controlled Water table Management (CWM) is being investigated as a possible 'Best Management Practice', to reduce drainage volumes and salt loads.

During 2000–2002 a trial was conducted on a 15 ha subsurface drained vineyard. This compared a traditional unmanaged subsurface drainage system with a controlled drainage system utilizing weirs to maintain water tables and changes in irrigation scheduling to maximize the potential crop use of a shallow water table. Drainage volumes, salt loads and water table elevations throughout the field were monitored to investigate the effects of controlled drainage on drain flows and salt loads.

Results from the experiment showed that controlled drainage significantly reduced drainage volumes and salt loads compared to unmanaged systems. However, there were marked increases in soil salinity which will need to be carefully monitored and managed.

Key words: controlled drainage, drainage water salinity, grapevines, soil salinity, water table management

Introduction

In the Murrumbidgee Irrigation Area (MIA) the development of high water table areas has been a major concern. Within the horticultural areas large losses in agricultural production have been experienced through waterlogging and salinisation throughout their history. Extensive subsurface drainage schemes have been implemented and currently 70% (12 000 ha) of all horticultural areas are protected with subsurface drainage, (Polkinghorne, 1992). The success in preventing waterlogging and salinisation is clearly evident and benefits from an agronomic perspective have been reported in a number of studies (Talsma and Haskew, 1959; van der Lely, 1978). However, a major effect, which was not envisaged at the time of design and development of the subsurface drainage systems, was the environmental consequences associated with disposal of saline drainage water.

Major environmental problems are now emerging due to the secondary effects associated with land drainage. These include contamination due to sediment, nutrients and pesticides found in drainage waters (Bowmer et al., 1998) and problems associated with saline drainage water (Blackwell et al., 2000; van der Lely and Ellis, 1974; van der Lely, 1984; van der Lely and Tiwari, 1995). These impacts affect both instream ecosystems as well as downstream consumptive users. Within the MIA the issues and restrictions on drainage water disposal have come from problems faced by downstream consumptive water users in the Wah Wah Irrigation Area, whose irrigation water contains drainage water from the Murrumbidgee Irrigation Area. Due to these pressures, options for reducing the salt load from subsurface drainage systems in the MIA are being investigated.

In reviewing options for reducing subsurface drainage salt loads it is interesting to assess how subsurface drainage systems have been implemented in the past and the associated outcomes. Figure 1 compares traditional implementation of a subsurface drainage system and the outcomes, with that of drainage implementation that also considers drainage water quality. With traditional implementation no management occurs after installation with systems simply left to operate continuously. This has led to extensive problems with large volumes of drainage water being generated and hence disposal problems plus associated low irrigation water use efficiency (Christen et al., 2001).

Figure 1 also shows the alternative process of subsurface drainage design when drainage water quality and volume are considered, with a view to creating a sustainable irrigation and drainage system, both agriculturally and environmentally. This process involves considering at an early stage the off-site consequences of subsurface drainage and incorporating these factors into the design process. Although alternative designs can produce more environmentally acceptable drainage systems their application is limited to new drainage installations. In areas with existing subsurface drainage, options need to be considered which modify the management of the drainage system to minimise off-site environmental impacts. Modifying new or existing systems to incorporate water quality targets is commonly referred to as

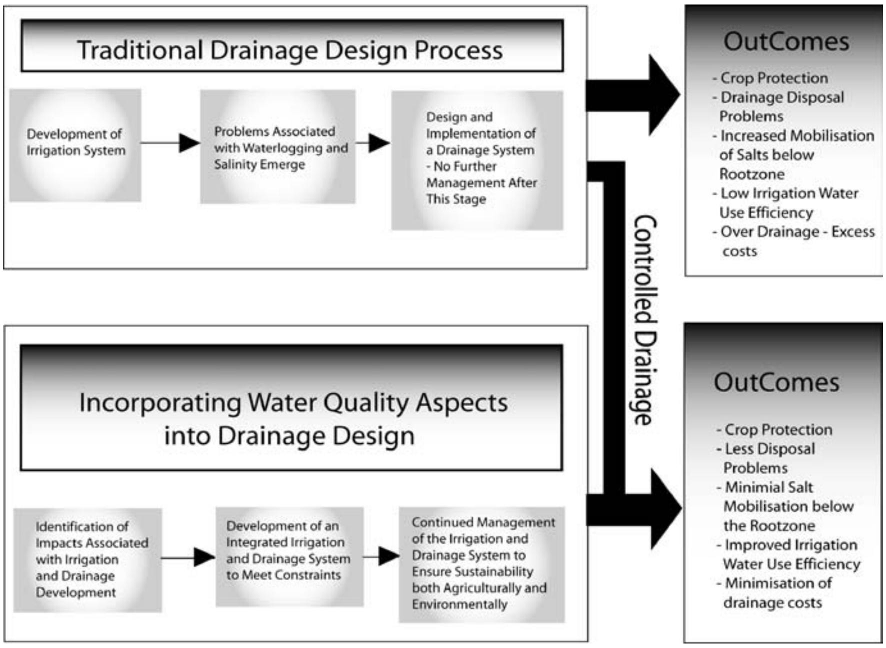


Figure 1. Subsurface drainage design processes from a past and future perspective.

controlled drainage (Ayars et al., 1997; Christen et al., 2001; Thomas et al., 1992).

The large majority of horticultural areas in the MIA already have subsurface drainage with no management of the drainage systems. Therefore, application of controlled drainage practices may have significant potential to reduce salt loads generated by these existing systems.

While previous field studies on controlled drainage in other areas of the world have shown potential for drainage volume and hence salt load reduction in semi-arid areas (Ayars, 1996; Ayars et al., 1999), these trials have been undertaken on annual crops. In the MIA, subsurface drained lands are associated with perennial horticultural crops (grapevines, citrus, prunes, peaches). This work was undertaken to assess the possible benefits associated with the application of controlled drainage management to perennial crops in the MIA.

The specific aim of this research was to investigate the effects of controlled drainage on subsurface drainage volumes, salt loads, water tables and root zone soil salinities in an irrigated winegrape vineyard.

Materials and methods

The experimental site was located in the Murrumbidgee Irrigation Area in South Eastern Australia which lies at latitudes 34° S and longitude 146° E

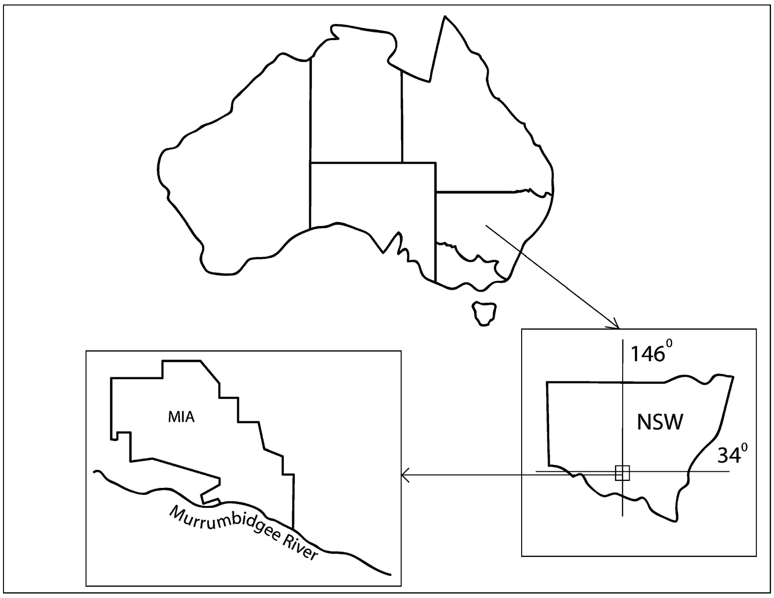


Figure 2. Location of MIA.

to the north of the Murrumbidgee River, Figure 2. The MIA is irrigated from water diverted from the Murrumbidgee River, supplied by large catchment dams located in the Snowy Mountains. The MIA has total farm area of 4 80 000 ha and accounts for 40% of grape production in New South Wales (NSW).

Experimental site

The vineyard was previously used for rice production before conversion to wine grapes 7 years prior to the installation of a subsurface drainage system in November 2000. The grapevines (*Vitis vinifera*) consist of a mixture of cultivars; Cabernet Sauvignon and Semillon. Surrounding areas are planted to a mixture of horticulture, rice and pastures all of which are irrigated.

The soil was identified as an Alfisol, in the Red–Brown Earth's of the Great Soil Groups of Australia outlined by Stace (1968). The surface soil is a shallow loam (0.1–0.3 m) and passes into a clay loam at a depth of 0.6 m. The deeper subsoil varies from a dark brown to red–brown in color and is associated with alternating sandy and clayey layers. Both soft and hard carbonates are present.

Drainage system layout

Subsurface drainage was installed at the site in November 2000. Drain spacings were calculated using the design procedures outlined by Talsma and

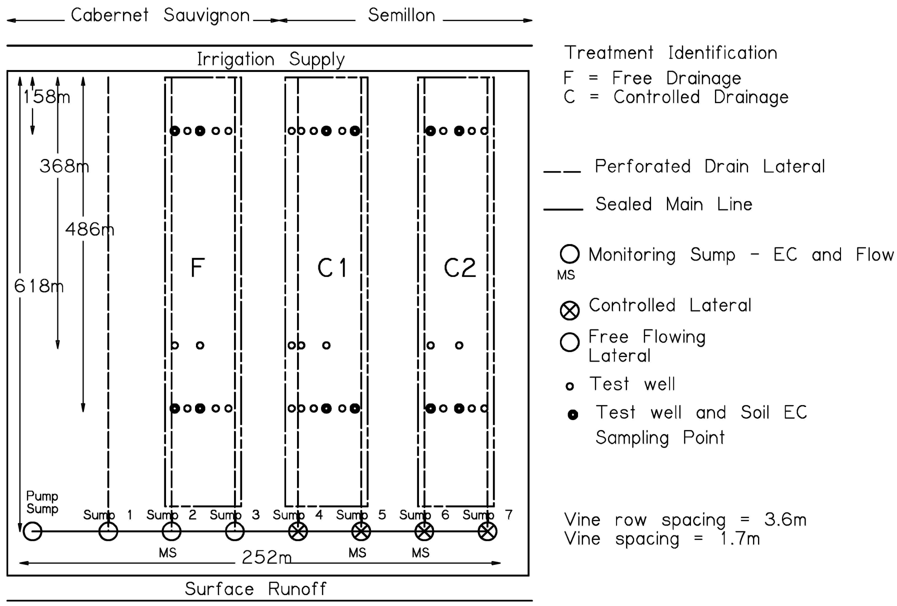


Figure 3. Experimental layout of field site showing drainage system and drainage treatments.

Haskew (1959), which led to a design spacing of 36 m at a depth ranging from 1.8 to 2.2 m. Perforated high density polyethelene pipe (0.1 m dia.) was used for laterals and the main was sealed (0.15 m dia.). A gravel envelope was used on all laterals. Inspection sumps were installed at the junction of each lateral to the main.

Experimental design

Two treatments were implemented at the site, ‘controlled drainage’ and ‘uncontrolled drainage’. The uncontrolled treatment area was on drain laterals 1 to 3 (Figure 3) where the Cabernet Sauvignon variety was grow, (plot F). The controlled drainage area was on drain laterals 4 to 7 where the Semillon variety was grown, (plots C1 and C2). The selection of these areas was based on the vine variety. Red grape varieties such as Cabernet Sauvignon typically require periods of water stress to improve grape quality hence a high water table would not be beneficial. White varieties such as Semillon do not require any periods of water stress, thus this area was chosen for the controlled drainage.

The controlled drainage treatment was implemented by placing risers on the drainage laterals where they entered the inspection sumps to prevent drainage occurring once the water table depth was greater than 1 m below the soil surface, Figure 4. The uncontrolled drain laterals had no control

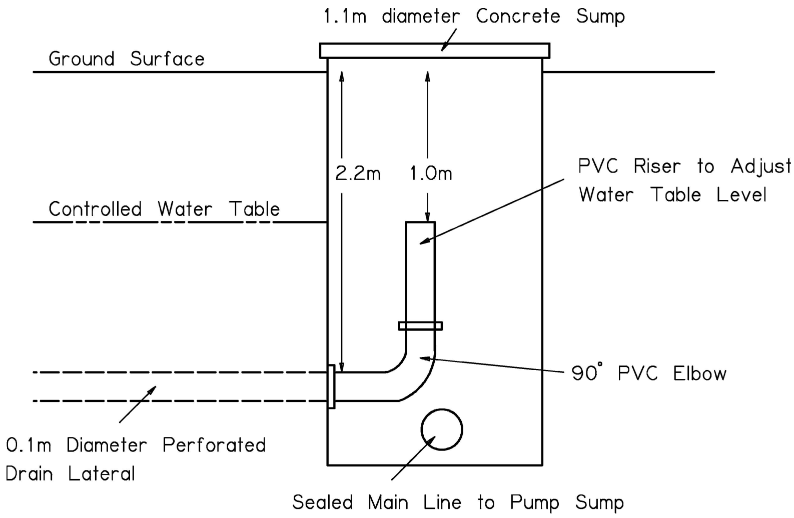


Figure 4. Cross-section of inspection sump with pipe riser on lateral drain.

structures and thus could flow freely and draw the watertable down to drain depth.

Monitoring

Monitoring of drain flow volumes and salinity was undertaken at sumps 2, 5 and 6. Test wells to monitor the watertable position were installed at three points across each treatment, Figure 3.

The test wells were 2.2 m deep pipes slotted from the bottom to within 0.3 m of the surface. These had a gravel envelope around the slotted area and a bentonite plug for the top 0.3 m to prevent surface water entry. These were measured at daily intervals before and after irrigation events and then at increasing intervals until the next irrigation. Drainage flows were measured manually from each lateral and salinity of the drainage water measured in the field using a hand held electrical conductivity meter. Drainage flows and electrical conductivity were measured at two hour periods during the irrigation period and then at increasing intervals until flow had ceased.

Water applied to the field was measured using 0.15 m diameter circular flumes (Samani et al., 1991) located in the furrows at the supply and runoff ends of the treatments. Flume readings were taken at 1 h intervals.

Soil salinity was monitored over the experimental period by taking soil cores to drain depth (1.8 m) at the start and end of the 2000/01 season and end of the 2001/02 season. The soil samples were dried and ground and electrical conductivity measured on 1:5 soil water suspensions. The coring locations are shown in Figure 3.

Results

Irrigation events which produce higher water table recharge emphasize the major differences between controlled and uncontrolled drainage systems. During the course of the experimental monitoring period the first irrigation of the 2000/2001 irrigation season produced the greatest recharge. This event has been presented in the results to demonstrate the differences in water tables, drain flow and salt loads due to implementation of controlled drainage.

Water tables

Average water table elevations for a 17 day period following application of 143 mm of irrigation water at the first irrigation of the 2000/2001 irrigation season are shown in Figure 5.

In the controlled drainage plots the water table rose more rapidly and remained higher for longer than the free drainage plot. The time that the average water table depth was above specified depths for a 17 day period between the start of the 1st irrigation and the commencement of the 2nd irrigation is shown in Table 1. It can be seen that the controlled drainage plots (C1, C2) had a higher proportion of time with the water table depth above 1.5 m, allowing potential beneficial use by the crop. The controlled drainage did not significantly increase the time the water table was above 1 m, hence waterlogging protection was still provided.

The control structures placed on the drainage laterals were effective in maintaining a higher water table in the controlled drainage plots, which had a

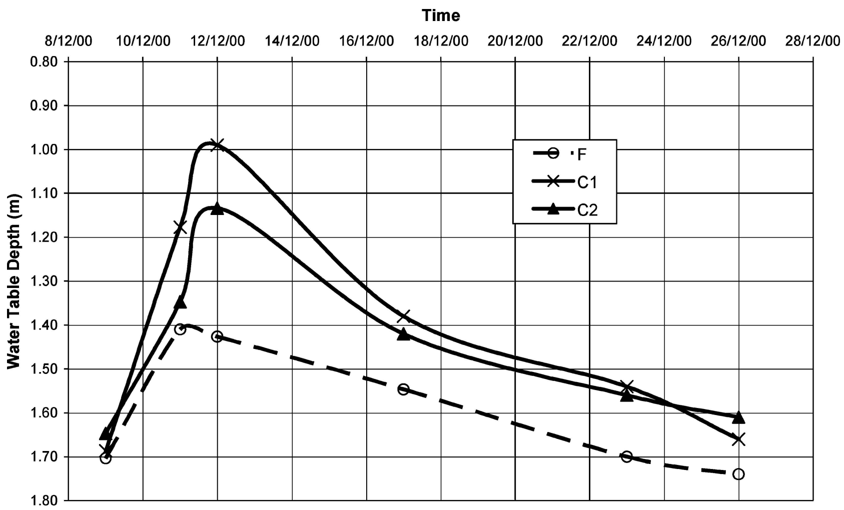


Figure 5. Average water table height under F, C1 and C2 treatments following 1st irrigation.

Table 1. Water table depth duration between the 1st and 2nd irrigation.

	Number of days		
Water table depth	F	C1	C2
<1 m	0	1	0
1 to 1.5 m	5	11	11
>1.5 m	12	5	6

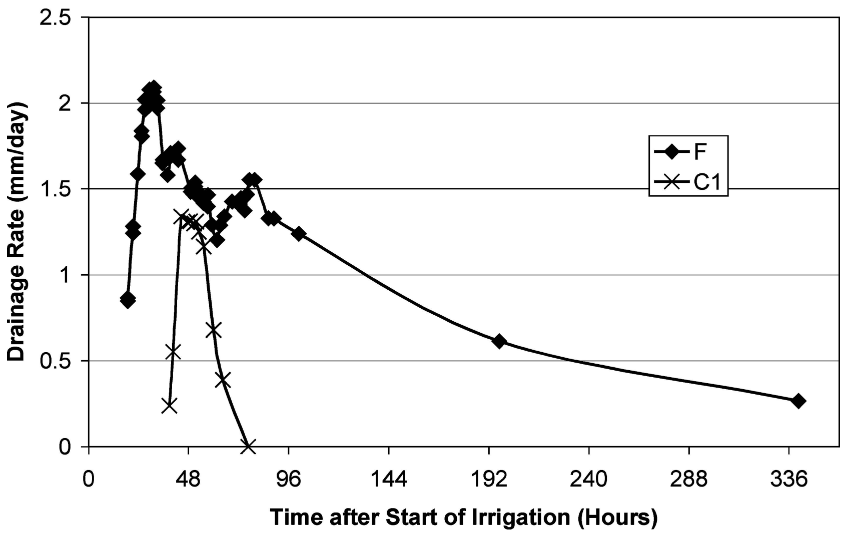


Figure 6. Drainage during the1st irrigation of the 2000/2001 irrigation season.

significant effect on the drainage volumes and salt loads as shown in the next section.

Drain flow and salt loads

The drain discharge hydrographs during the 1st irrigation of the 2000/2001 irrigation season are shown in Figure 6. The controlled drainage resulted in significantly less drainage than free drainage. The controlled drains flowed for between 38–41 h, flows from the free drainage plot occurred for over 320 h, flowing continuously until the next irrigation event. Peak discharges with controlled drainage were lower and occurred about 12 h later than the free drainage treatment. This was the extra time required to fill the profile to the pipe weir depth before drainage could occur.

The different flow volumes had a large effect on the salt loads, Table 2. The free drainage removed significantly more salt than the controlled drainage

Table 2. Total drainage, average salinity and salt load for the 1st irrigation of 2000/2001 irrigation season.

Treatment	Drainage (mm)	Average salinity (dS/m)	Salt removed (kg/ha)
F	9	2.84	164
C1	1	1.85	12
C2	1	2.03	13

treatment. The total irrigation applied was 143 mm (Salinity of 0.1 dS/m) resulting in a salt application of 77 kg/ha. It can be seen that free drainage removed more salt from the profile than was applied in the irrigation water.

Removing the pipe weirs

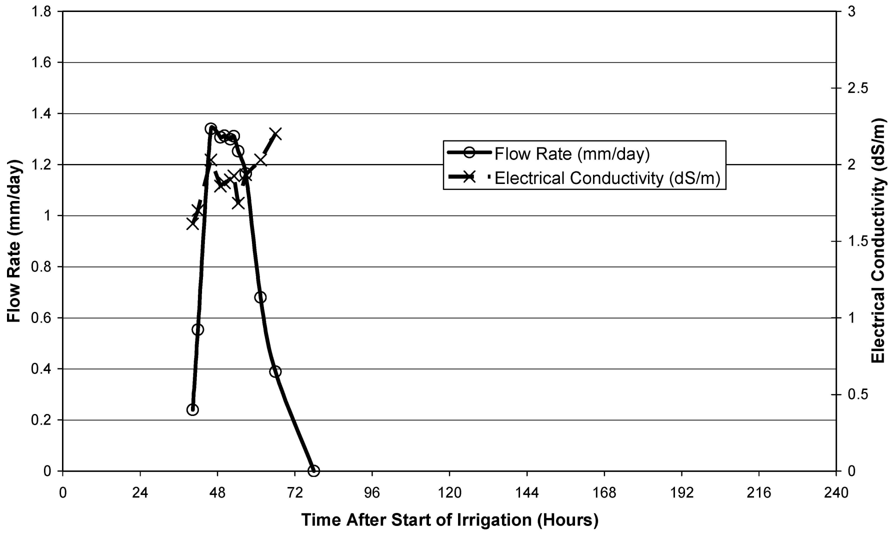
For the second irrigation event of the 2001/2002 irrigation season, the pipe weirs were removed from the controlled drainage laterals to allow the drains to flow freely and salt leaching to occur. This provided the opportunity to compare the performance of those laterals with and without pipe weirs. This event can be compared to the 1st irrigation event of the 2000/2001 irrigation season as a high recharge event. Drain discharges and electrical conductivities from these two events are shown in Figure 7 for the C1 plot.

It can be seen that the control structures had a significant effect in reducing the drainage discharge volumes. The irrigation applied was four times more when the pipe weirs were in place on the laterals and yet drainage volumes were still significantly reduced compared to the period when control structures were removed (Table 3).

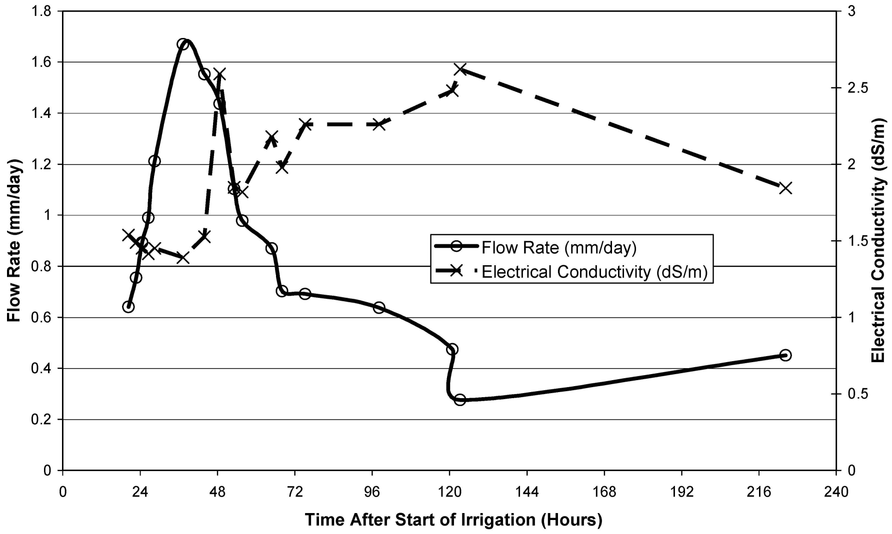
It can be clearly seen from Table 3 that the control structures had a significant effect on reducing the drain flow and subsequently the amount of salt removed from the drainage system.

Drainage and salt loads over two year monitoring period

The previous sections have highlighted the effects of controlled drainage during high recharge periods and showed significant differences between drainage volumes and salt loads during these periods. Over the 2 year monitoring period which included two irrigation seasons the controlled drainage treatments were found to significantly reduce drainage volumes and salt loads. Total drained amounts and the volume of salt removed from the plots over two irrigation seasons is shown in Table 4. Salt volumes were calculated on the basis of relationship of 1 $dS/m = 640$ mg/L (Tanji, 1990) for the irrigation and drainage waters and salt content of the rainfall was taken as 6.9 mg/L based on studies undertaken by Blackburn and McLeod (1983).



(a)



(b)

Figure 7. (a) C1 drainage flows and electrical conductivity of drainage water after irrigation application of 143 mm with controlled drainage structures in place during 1st irrigation of the 2000/2001 irrigation season (b) C1 drainage flows and electrical conductivity of drainage water after irrigation application of 32 mm with no drainage control structures in place during the second irrigation of the 2001/2002 irrigation season.

Table 3. Water applied and percentage drained during controlled and uncontrolled irrigations.

Plot	Irrigation event	Drainage status	Irrigation applied (mm)	Drainage (%)
C1	1st Irrigation 2000/2001	Controlled	143	1
	2nd Irrigation 2001/2002	Uncontrolled	32	6
C2	1st Irrigation 2000/2001	Controlled	93	1
	2nd Irrigation 2001/2002	Uncontrolled	24	8

Table 4. Drainage as percentage of irrigation and salt loads as percentage of salt applied for two seasons.

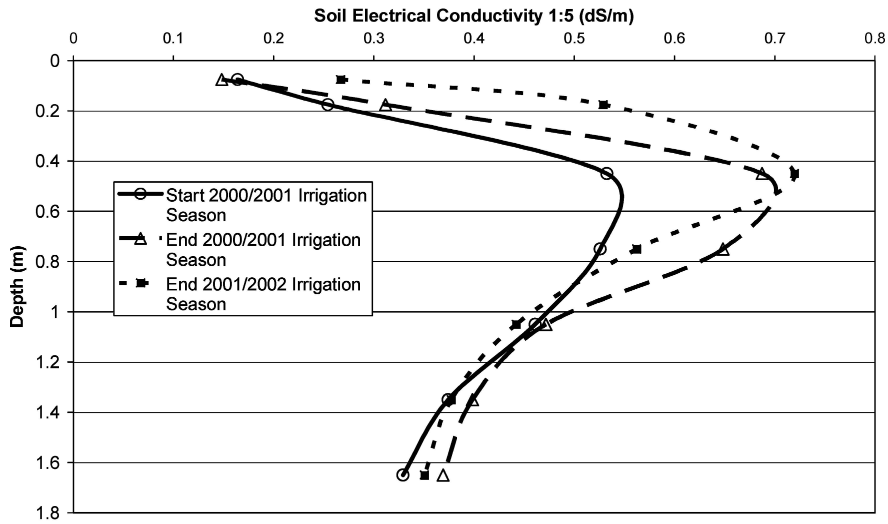
Plot	Irrigation (mm)	Drainage (%)	Salt load (%)
F	638	6	101
C1	694	0.5	5
C2	665	0.5	6

It can be seen that the free drainage plot (F) had significantly higher drainage and salt loads than the controlled drainage plots (C1 and C2). Drainage volumes measured during the experimental period were considerably lower than those typically found in subsurface drained fields in the area, due to significantly lower volumes of irrigation water applied to the vineyard than the area average. Previous monitoring of tile drainage systems in the area reported by Christen and Skehan (2001) and van der Lely (1993) measured drainage volumes between 14–22% of applied water. The large differences between these studies and results shown above were due firstly to irrigation volumes being considerably less in this study <350 mm/year compared to 600 to 1000 mm/year for the previous studies and secondly rainfall during the experimental period (322 mm for 2001 and 208 mm for 2002) was well below the long-term average (396 mm).

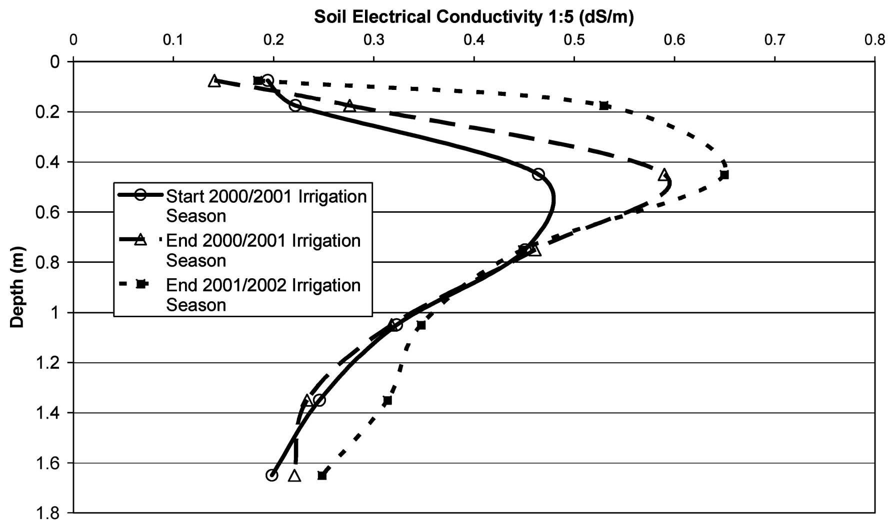
It can be clearly seen that controlled drainage was effective in increasing water table heights in the controlled drainage treatments and this reduction in drainage has the benefit of reducing disposal problems due to the decreased drainage volumes and subsequent lower salt loads. However, two issues need to be considered regarding the suitability of controlled drainage. Firstly, if controlled drainage management is to be successful then it relies on the crop being able to successfully use water from the water table to meet part of its evapotranspiration requirements. Secondly, it can be seen from Table 4 that salt accumulation occurred in the controlled drainage treatments (only 5–6% of applied salt was removed). Therefore, the effects of controlled drainage on soil salinity levels need to be thoroughly investigated to assess the sustainability of the system.

Soil salinity

A general trend was observed over the entire field of increasing soil salinity. This can be attributed to the upflux of water from the groundwater table (average electrical conductivity of 5 dS/m), which occurred to meet crop water demands. Figure 8 shows changes in the soil salinity profile over the experimental period.



(a)



(b)

Figure 8. Soil salinity changes during the experimental period in (a) F treatment, (b) C1 treatment and (c) C2 treatment. (*Continued on next page*)

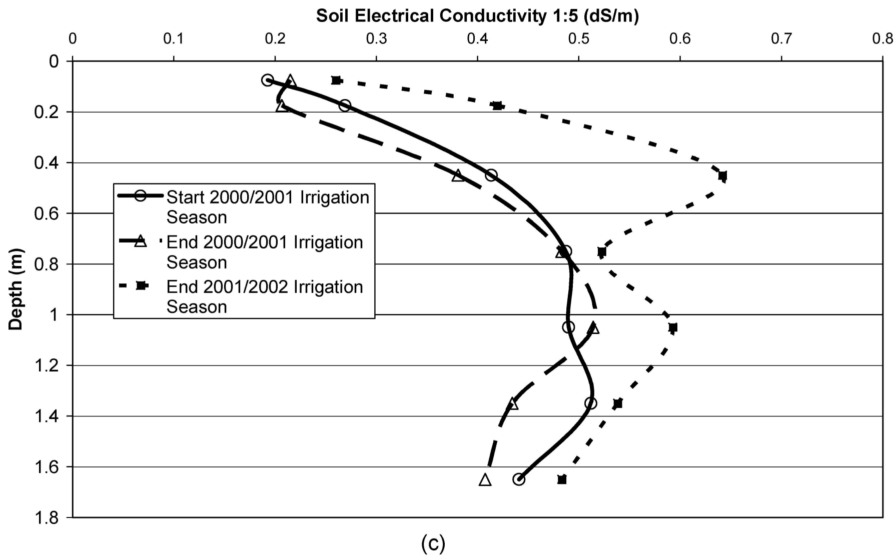


Figure 8. (*Continued*)

Soil salinity generally increased in all layers. Higher increases were observed in the upper soil layers, particularly in the 0–0.3 m and 0.3–0.6 m layers. Both the free drainage and controlled drainage areas experienced an increase in soil salinity over the experimental period, due to the large irrigation deficits that were present, promoting capillary up-flow from the water table.

Although the increases in soil salinity did not reduce the measured vine yields, it is apparent that sustainability issues will need to be carefully considered when implementing controlled drainage. Implementation of any strategies which aim to increase plant water use from a shallow groundwater source will need to carefully consider soil salinity increases and implement appropriate monitoring. Although the increase in soil salinity is a drawback associated with controlled drainage, mitigation of its effects should be possible by implementing periods of leaching between periods of controlled drainage, e.g. allowing free drainage during the winter to allow leaching by rainfall, or allow free drainage during the first irrigation of the season.

Conclusions

1. Water table regimes and subsequently drain flow characteristics are significantly changed under controlled drainage practices.
2. Controlled drainage has the potential to reduce drainage volumes and subsequently salt loads. This can help reduce negative downstream effects associated with subsurface drainage.

3. The potential for root zone salinisation will be a major consideration when developing management practices to ensure the sustainability of controlled drainage. Careful monitoring and management will be required when implementing controlled drainage.

Acknowledgements

We would like to thank Land and Water Australia and their National Program for Irrigation Research and Development for providing funding for a post graduate scholarship for the first author. We would also like to thank Mr John Dal Broi for supplying the experimental site and his co-operation. Technical assistance from Roy Zandona, Brad Fawcett and David Smith is also gratefully acknowledged.

References

Ayars, J.E. 1996. Managing irrigation and drainage systems in arid areas in the presence of shallow groundwater: Case studies. *Irrigation and Drainage Systems* 10: 227–224, Kluwer Academic Publishers.

Ayars, J.E., Grismer, M.E. & Guitjens, J.C. 1997. Water quality as design criterion in drainage water management systems. *Journal of Irrigation and Drainage Engineering* 123(3): 154–158.

Ayars J.E., Hutmacher, R.B., Schoneman, R.A., Soppe, R.W.O., Vail, S.S. & Dale, F. 1999. Realizing the potential of integrated irrigation and drainage water management for meeting crop water requirements in semi-arid and arid areas. *Irrigation and Drainage Systems* 13: 321–347, Kluwer Academic Publishers.

Blackburn, G. & McLeod, S. 1983. Salinity of Atmospheric Precipitation in the Murray-Darling Drainage Division, Australia. *Australian Journal of Soil Research* 21: 411–434.

Blackwell, J., Biswas, T.K., Jayawardane, N.S. & Townsend, J.T. 2000. *Irrigation – Getting the Edge*, GRDC Irrigation Update, Mathoura Bowling Club, NSW, 16 August.

Bowmer, K.H., Korth, W., Scott, A., McCorkelle, G. & Thomas, M. 1998. *Pesticide Monitoring in the Irrigation Areas of South Western NSW* 1990–1995, CSIRO Land and Water, Technical Report 17/98.

Christen, E.W. & Skehan, D. 2001. Design and Management of Subsurface Horizontal Drainage to Reduce Salt Loads. *Journal of Irrigation and Drainage Engineering* 127(3).

Christen, E.W., Ayars, J.E. & Hornbuckle, J.W. 2001. Subsurface drainage design and management in irrigated areas of Australia. *Irrigation Science* 21: 35–43.

Polkinghorne, C. 1992. Tile Drainage in the MIA. *Farmers Newsletter*.

Samani, Z., Jorat, S. & Yousaf, M. 1991. Hydraulic Characteristics of Circular Flume. *Journal of Irrigation and Drainage Engineering* 117(4), ASCE.

Stace, H.C.T., Hubble, G.D., Brewer, R., Northcote, K.H., Sleeman, J.R., Mulcahy, M.J. & Hallsworth, E.G. 1968. *A Handbook of Australian Soils*, Glenside, South Australia.

Talsma, T. & Haskew, H.C. 1959. Investigation of Water Table Response to Tile Drains in Comparison with Theory. *Journal of Geophysical Research* 64(11).

Tanji, K.K. 1990. *Agricultural salinity assessment and management*, ASCE Manuals and Reports on Engineering Practice No. 71, American Society of Civil Engineers, 345 East 47th street, N.Y. 10017.

Thomas, D.L., Hunt, P.G. & Gilliam, J.W. 1992. Water table management for water quality improvement. *Journal of Soil Water Conservation* 47(1): 65–70.

Van der Lely, A. 1978. Artifical Subsurface Drainage in the MIA. In Storrier and Kelly (Eds) *The Hydrologeology of the Riverine plain of South East Australia*, Australian Society of Soil Science Inc, Riverina Branch.

Van der Lely, A. 1984. *Options for salt management in the MIA – Principles, Requirements, Consequences, Constraints*, Water Resources Commission Report, Griffith.

Van der Lely, A. & Ellis R.L. 1974. *Water from tile drainage systems in the MIA – Salinity Aspects*, In Agricultural Engineering Conference, Sydney, NSW, IE Australian Agricultural Engineering Branch, University of New South Wales.

Van der Lely, A. & Tiwari, A. 1995. *Evaluation of Water table control options*, Appendix 4, Support Document to the MIA LWMP.